Appendix M. Summary Report Global Analysis Of Macondo 9 7/8-In X 7-In Production Casing 4992 ft Water Depth, GoM (for Macondo Well Investigation) (from Stress Engineering)

SUMMARY REPORT
GLOBAL ANALYSIS OF
MACONDO 9 7/8-in x 7-in PRODUCTION CASING
4992 FT WATER DEPTH, GOM
(FOR MACONDO WELL INVESTIGATION)
PN1101197

Prepared for:

BP
Houston, Texas

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4992 FT WATER DEPTH, GOM
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TABLE OF CONTENTS

LIST OF TABLES

Page No.

LIST OF FIGURES

Page No.

1.0 PURPOSE

The primary objective of the global analysis is to determine the axial growth of the 9 7/8-in x 7-in production casing of the Macondo well in the Gulf of Mexico for the condition when the well is displaced with seawater after the negative test [1], and to determine the incremental pressure on the backside of the production casing that would cause the 9 7/8-in casing/casing hanger to unseat from its position in the wellhead, in the absence of a locking mechanism to keep the 9 7/8-in x 7-in casing tied to the wellhead.

Stress Engineering Services was contracted by BP, to assist them in their engineering efforts to assess in determining the pressure that would cause the 9 7/8-in casing/casing hanger/seal assembly to unseat from its position in the wellhead.

The casing system is constructed in ABAQUS, a multi-purpose finite element analysis software, and is loaded under self-weight during the casing installation procedure in 14-ppg mud, followed by cementing of the casing. This step produces the initial stress and deformation state from which the pressure to unseat the 9 7/8-in x 7-in casing is determined.

The condition after the negative test consists of displacing a portion of the 14-ppg mud in the production casing with seawater. The response is characterized primarily in terms of the additional pressure on the backside that causes initial lift-off of the 9 7/8-in casing hanger from the wellhead and the pressure to lift the top of the 9 7/8-in casing hanger by 6-in off its initial position in the wellhead.

To establish the veracity of the predicted response, the results are compared to hand calculations. The ABAQUS model response is shown to match the hand calculations with very good agreement.

BP supplied SES with a problem description, a detailed description of the casing, general specifications for the analytical approach and specific cases to analyze.

The key findings are summarized in table 1 below:

Table 1: Summary of Findings

	Bottom of the Model	External Pressure (psi)	Net Top Displacement (in)	ΔDisplacement/ΔPressure
Hand Calculations Thick Wall Theory	Top of the 7" Casing Cement	453.0	0.0	**
		516.9	6.0	0.094
	Bottom of the 7" Casing Cement	445.0	0.0	**
		501.8	6.0	0.106
Hand Calculations Thin Wall Theory	Top of the 7" Casing Cement	440.2	0.0	**
		504.6	6.0	0.093
	Bottom of the 7" Casing Cement	432.5	0.0	**
		489.7	6.0	0.105
ABAQUS Model	Top of the 7" Casing Cement	440.6	0.0	**
		505.1	6.0	0.093
	Bottom of the 7" Casing Cement	432.7	0.0	**
		490.0	6.0	0.105

An additional 129 psi pressure is required to overcome an assumed 32 kips of frictional resistance between the wellhead and the seal assembly.

An additional case was also investigated based upon the assumption that the casing is unconstrained at the bottom due to the cement not being able to sustain a shear bond. It was determined that a pressure influx of approximately 258 psi would initially lift-off the 9 7/8-in casing hanger from its position in the wellhead.

2.0 MODELING ASSUMPTIONS

ABAQUS is a general-purpose finite element program, which can model non-linearity of geometry, material properties, and spring definitions. Version 6.5, which was used for this work.

The analysis was performed with the following data/assumptions:

- The analysis does not attempt to simulate the failure process of a specific mode at a specific component.
- A global ABAQUS beam model of the casing system, and wellhead was constructed.
- Quasi-static analysis was performed (dynamic effects are not included).
- Linear elastic material properties are used.
- Beam elements (PIPE31H) are used to model all pipe sections.

The finite elements utilized were the ABAQUS PIPE31H beam element. This is a three-dimensional beam element that models a pipe in space. This element accounts for internal and external hydrostatic pressure effects, using the HP option. The HP option calculates the correct hoop stresses in the pipe due to fluid pressure, which then calculates the correct von Mises stress without any further post-processing. Furthermore, ABAQUS version 6.5 allows for pressure end loads to be modeled correctly in instances where there is a change in internal or external diameter of the riser.

The HP option provides an allowance for end loads and varying hydrostatic pressures in the production casing and its correct use leads to ensuring that the actual and effective tension distribution are correct.

The elements used in the ABAQUS model are treated with thin wall pipe theory formulation. To compare the veracity of the results and to understand the deviation from thick wall pipe theory (Lame's equations), ABAQUS results were compared to hand calculations based on thin and thick walled formulations.

For both, thin and thick wall theory, the axial strain εa is given by:

$$\varepsilon_a = \frac{1}{E}\left(\frac{T_a}{A} - v(\sigma_\theta + \sigma_r)\right) \qquad \textbf{Equation 1}$$

where,

ν = Poisson's ratio = 0.3

A = pipe cross sectional area

E = Young's modulus of the material

Ta = Actual tension

σ_θ is the hoop stress and σ_r is the radial stress, in thin wall theory the hoop stress is equal to:

$$\sigma_\theta = \frac{pr}{t} \qquad \textbf{Equation 2}$$

where,

t = thickness of the pipe

r = radius of the pipe

p = is the pressure across the pipe wall.

In thick wall theory the radial and hoop stresses at any radial location, r, are given by the following formulas:

$$\sigma_r = \frac{P_i a^2 - P_o b^2 - (P_i - P_o)(a^2 b^2 / r^2)}{b^2 - a^2}$$

Equation 3

$$\sigma_\theta = \frac{P_i a^2 - P_o b^2 + (P_i - P_o)(a^2 b^2 / r^2)}{b^2 - a^2}$$

Equation 4

where,

σ_r = radial stress

σ_θ = hoop stress

r = radius

a = inner radius

b = outer radius

P_i = internal pressure

P_o = external pressure

3.0 SYSTEM CONFIGURATION

The details of the components modeled in the analysis are listed below in table 2:

Table 2: Casing Sizes

Production Casing Sizes	**Outer Diameter (in)**	**Thickness (in)**	**Dry weight per unit length (lb/ft)**
9 7/8-in	9 7/8-in	0.625-in	62.8 ppf
7-in	7-in	0.453-in	32 ppf

Other important system parameters include:

- The water depth = 4992-ft
- The location of the RKB above the mudline = 5067-ft
- The casing hanger seal elevation above the mudline = 8-ft
- The cross over between the 9 7/8-in x 7-in casing occurs at 7420-ft below the mudline.
- The bottom of the drillpipe is 3,310-ft below the mudline.
- The 7-in casing is fixed at 13,235-ft below the mudline.
- The diameter of the pressure bearing seal at the hanger = 18.635-in
- Based on discussion with DrilQuip [2], a value of 32-kips was chosen as the force required to overcome the hanger seal friction.

A schematic of the entire assembly is shown in Figure 1, 2 and 3, adapted from reference 1. Figure 1 shows the condition when the 9 7/8-in x 7-in casing is run in and landed in the wellhead in 14-ppg mud. Figure 2 shows the condition when the casing is cemented. For this study, the ABAQUS model is fixed at the top of the cement. To understand the sensitivity of the results to the loss in the strength of the cement shear bond, several cases were analyzed by assuming that the bottom of the cement being fixed. Figure 3 shows the contents of the system after the negative test.

It should be noted that the condition after the negative test scenario case considers that seawater is located above the location of the bottom of the drillpipe, i.e. there is no spacer in this column of fluid.

Note, that the hydrostatic pressure of the fluid in the 9 7/8 x 7-in casing includes the seawater pressure gradient down to the bottom of the drillpipe plus the gradient due to the 14-ppg mud below the bottom of the drillpipe to the bottom of the casing to the float collar.

Figure 4, shows the 9 7/8-in hanger and seal assembly with the hanger sealing diameter; the schematic in figure 5 show how pressure is reacted above and below the seal area. This is used in the pressure balance across the 9 7/8-in x 7-in casing hanger and seal assembly. In addition, Figure 6 shows the pressure bearing area at the 9 7/8-in x 7-in crossover. Note, that in both figures 5 and 6, the pressure P2 will include the hydrostatic pressure and any additional influx of pressure.

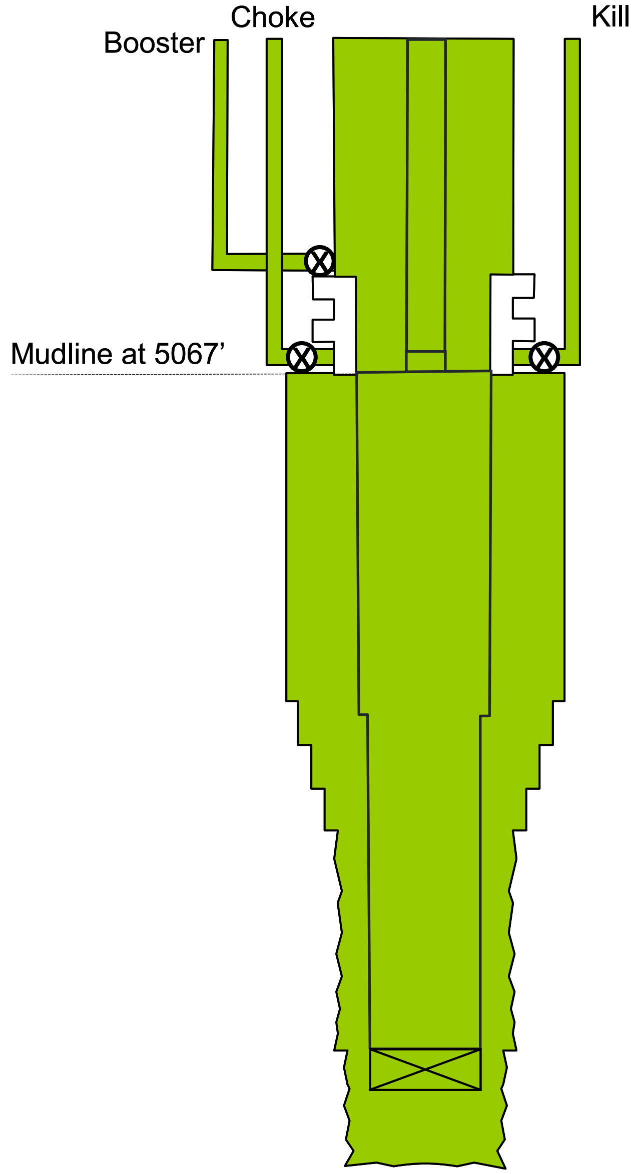

Figure 1: Production Casing Run on Drillpipe and Landed On Hanger in 14-ppg

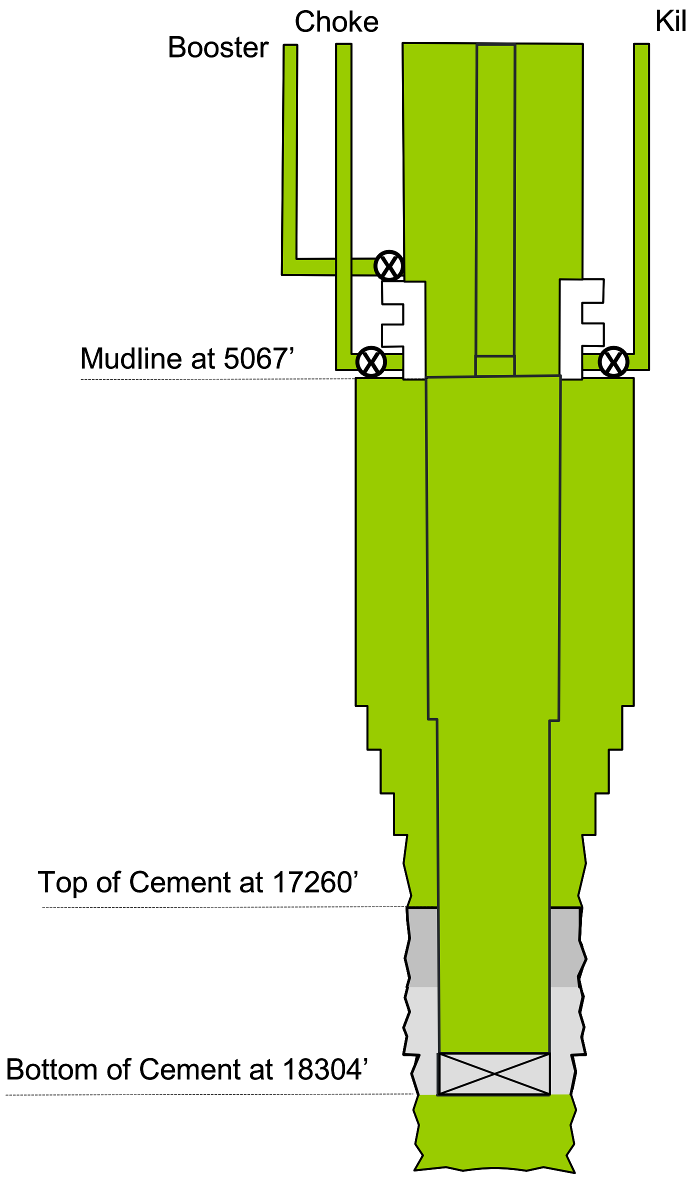

Figure 2: Production Casing Cemented

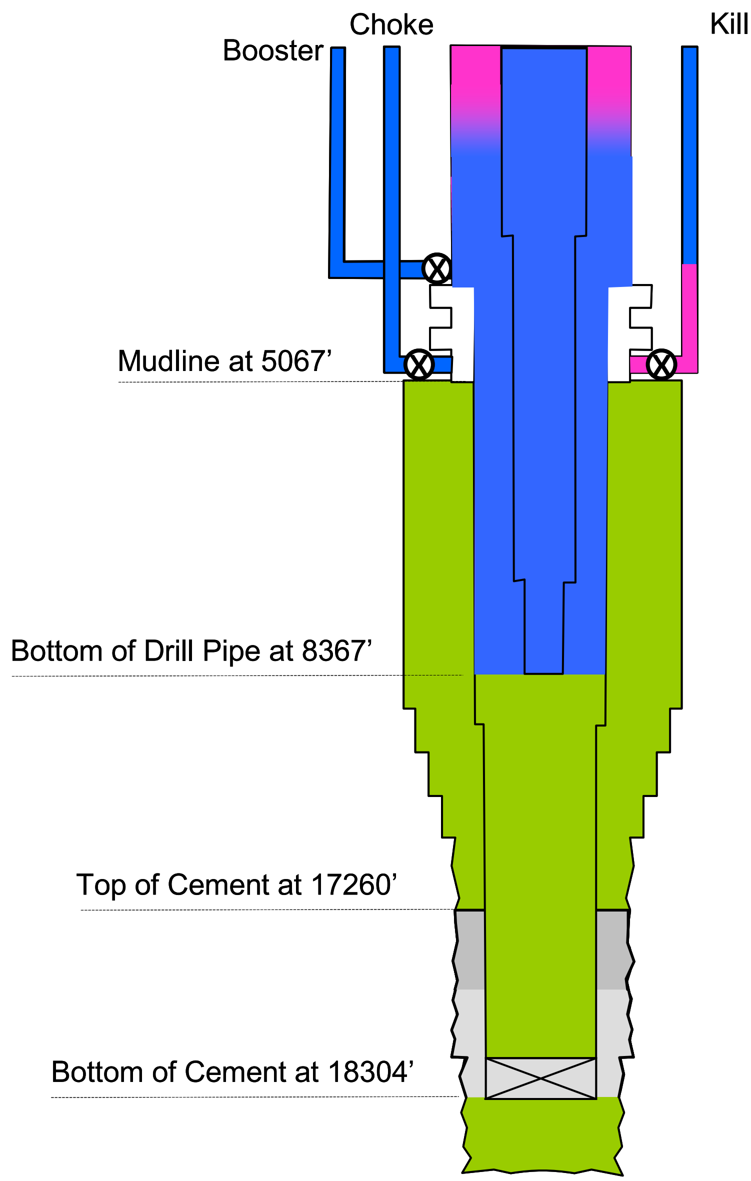

Figure 3: Configuration after Negative Test

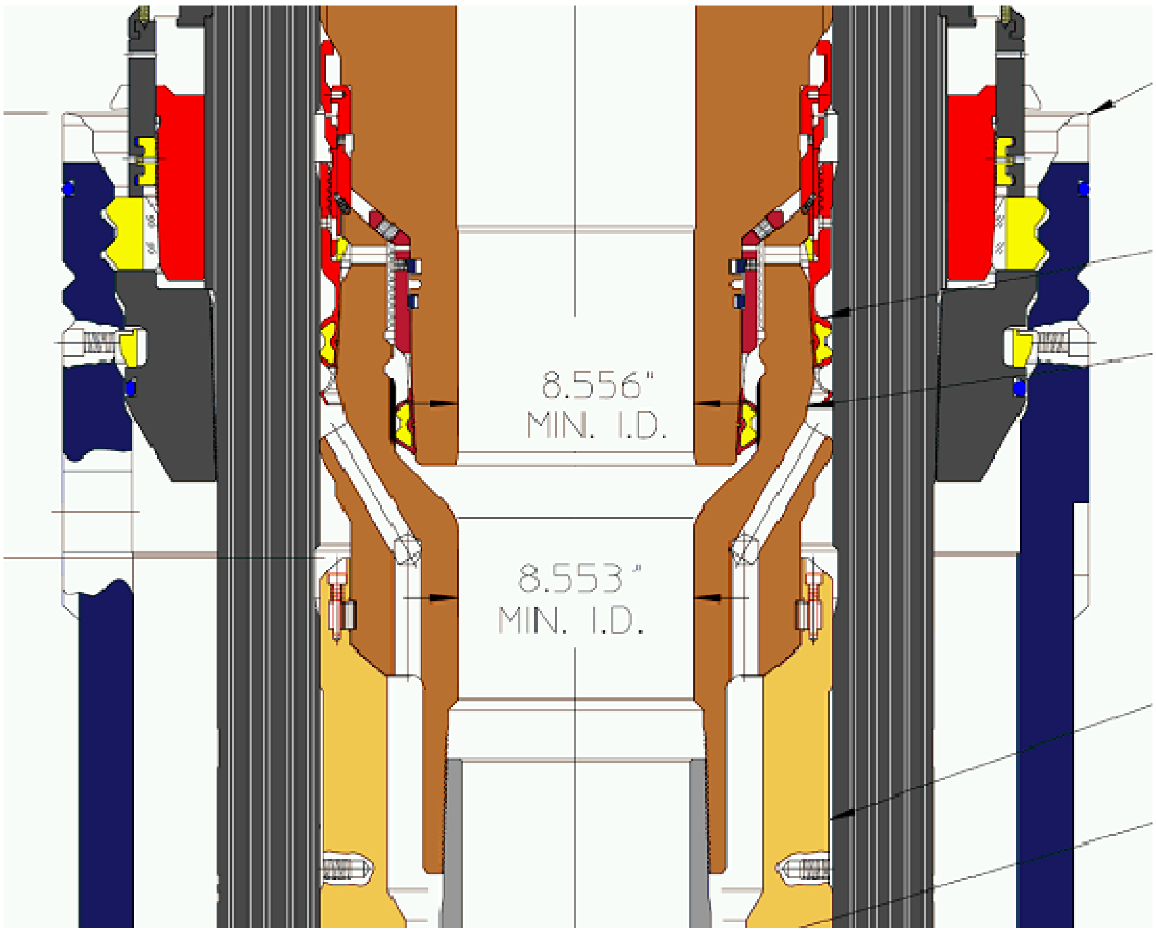

Figure 4: Casing Hanger and Seal Assembly Configuration at Wellhead

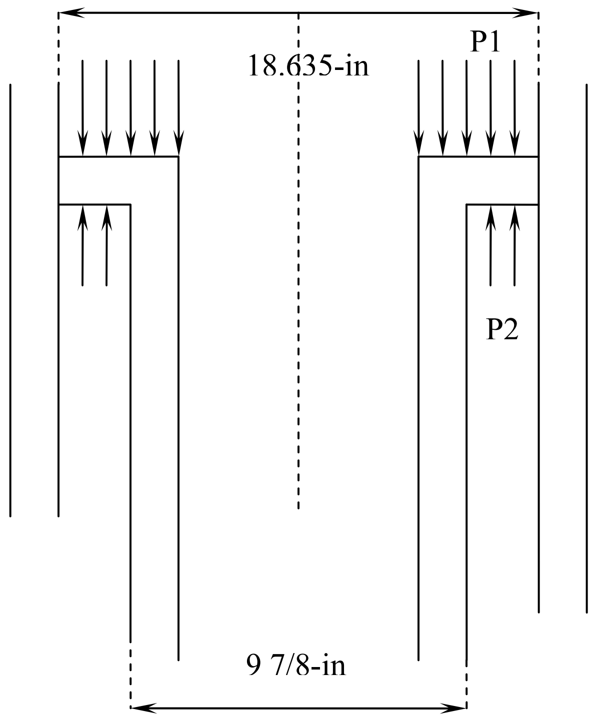

Figure 5: Pressure Bearing Areas at the Casing Hanger

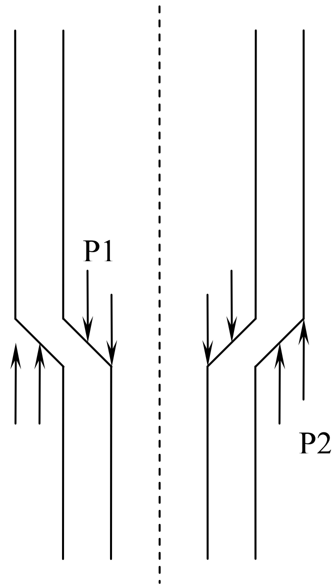

Figure 6: Pressure Bearing Areas on 9 7/8-in x 7-in Crossover

4.0 ANALYSIS STEPS

The ABAQUS model consists of the following steps that simulate the casing installation sequence:

1. Run 9 7/8-in x 7-in casing in 14-ppg mud and hang the 9 7/8-in casing hanger at the wellhead. In this scenario the top of the casing is fixed and the bottom of the casing is allowed to move axially (to accommodate stretch under self-weight). The effective tension at the bottom of the casing is zero; the actual tension at the bottom of the casing is compressive in nature. This condition captures the initial state of stress and deformation in the casing.
2. The location corresponding to the top of the cement is fixed (zero rotations and displacements).
3. The boundary condition at the casing hanger seal is modified to allow upward movement; this is facilitated by a bilinear spring introduced at this location to allow upward movement but no downward movement.
4. The HPE and HPI hydrostatic option is modified to account for the seawater gradient above the drillpipe and the effect of the sea water gradient on the 14-ppg mud below the seawater.
5. The pressure on the backside of the production casing is increased using PE option in ABAQUS.

Note, that in all steps, the end loads are accounted for at the seal diameter area and at the crossover between the 9 7/8-in x 7-in casing.

5.0 CASES CONSIDERED

The following cases are considered:

Table 3: Cases Considered for Global Analysis

Case #	Comments
1	Fixed at bottom of 7-in casing cement (with and without 32-kips seal friction resistance)
2	Fixed at top of 7-in casing cement (with and without 32-kips seal friction resistance)
3	Cement unable to sustain a shear bond with the 7-in casing

6.0 RESULTS AND DISCUSSION

A summary of the results from the global analysis follows:

CASE 1 (Bottom of 7-in Casing Cement Fixed):

The increase in pressure from an influx that would cause the casing hanger to initially lift-off is approximately **433 psi.**

The increase in pressure from an influx that would cause the casing hanger to lift-off by 6-in is approximately **490 psi.**

Note, that the above numbers does not include the additional 32-kips from seal friction; this is the frictional force between the seal and the inner diameter of the wellhead housing.

The additional pressure to overcome the 32-kips seal friction was found to be approximately **129-psi.**

The increase in pressure from an influx that would cause the casing hanger to initially lift-off, **including the seal friction effect,** is approximately **562 psi.**

The increase in pressure from an influx that would cause the casing hanger to lift-off by 6-in, **including the seal friction effect,** is approximately **619 psi.**

A summary of the results is shown in the table below and in Figure 7, overleaf.

Table 4: Case 1-Summary Results

	Bottom of the Model	External Pressure (psi)	Net Top Displacement (in)	ΔDisplacement/ΔPressure
Hand Calculations Thick Wall Theory	Bottom of the 7" Casing Cement	445.0	0.0	**
		501.8	6.0	0.106
Hand Calculations Thin Wall Theory	Bottom of the 7" Casing Cement	432.5	0.0	**
		489.7	6.0	0.105
ABAQUS Model	Bottom of the 7" Casing Cement	432.7	0.0	**
		490.0	6.0	0.105

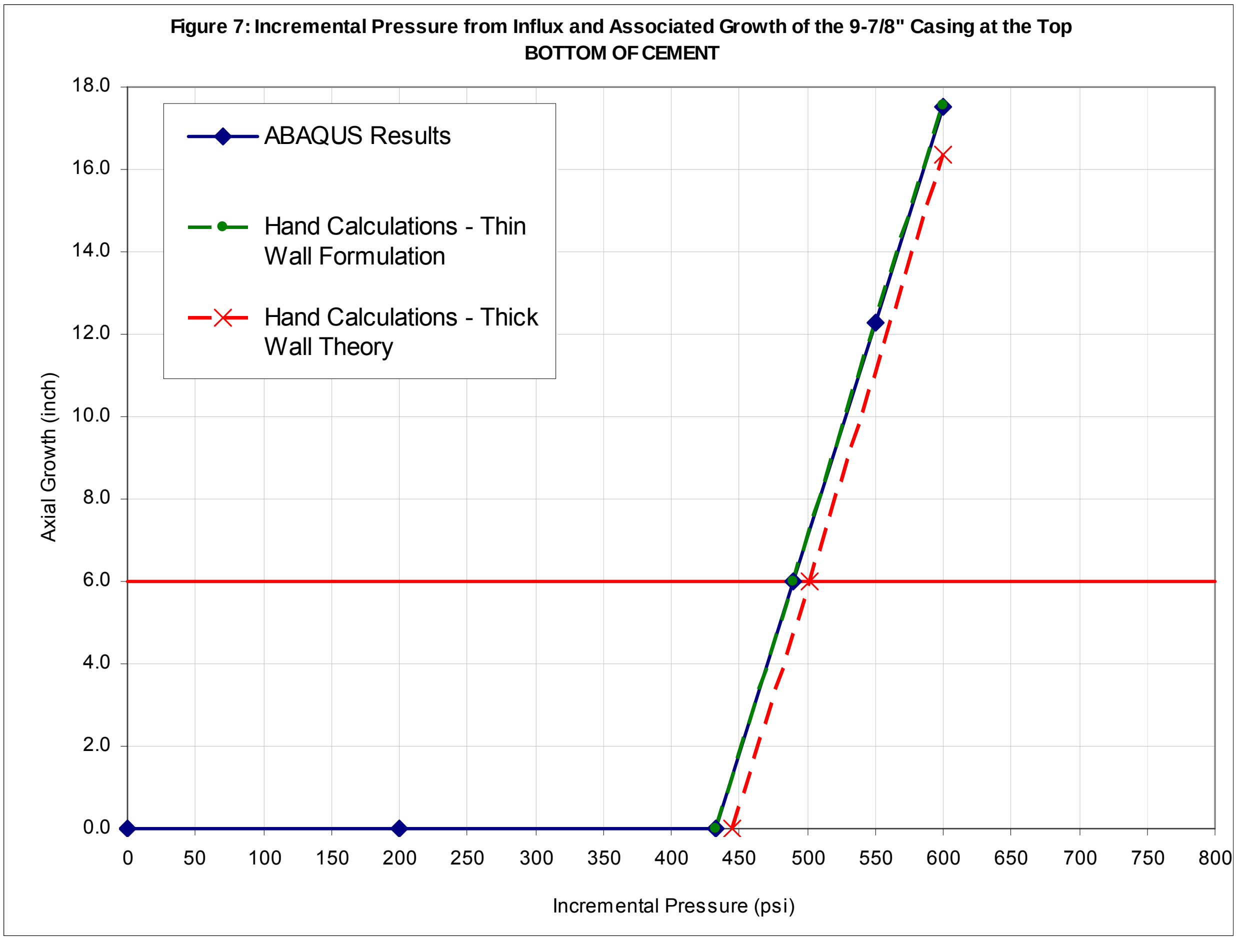

Figure 7: Graphical Representation of Results for Case 1

CASE 2 (Top of 7-in Casing Cement Fixed):

The increase in pressure from an influx that would cause the casing hanger to initially lift-off is approximately **440 psi.**

The increase in pressure from an influx that would cause the casing hanger to lift-off by 6-in is approximately **505 psi.**

Note, that the above numbers does not include the additional 32-kips from seal friction.

The additional pressure to overcome the 32-kips seal friction was found to be approximately **129-psi.**

The increase in pressure from an influx that would cause the casing hanger to initially lift-off, **including the seal friction effect,** is approximately **569 psi.**

The increase in pressure from an influx that would cause the casing hanger to lift-off by 6-in, **including the seal friction effect,** is approximately **634 psi.**

A summary of these results is shown in the table below and in Figure 8, overleaf.

Table 5: Case 2-Summary Results

	Bottom of the Model	External Pressure (psi)	Net Top Displacement (in)	ΔDisplacement/ΔPressure
Hand Calculations Thick Wall Theory	Top of the 7" Casing Cement	453.0	0.0	**
		516.9	6.0	0.094
Hand Calculations Thin Wall Theory	Top of the 7" Casing Cement	440.2	0.0	**
		504.6	6.0	0.093
ABAQUS Model	Top of the 7" Casing Cement	440.6	0.0	**
		505.1	6.0	0.093

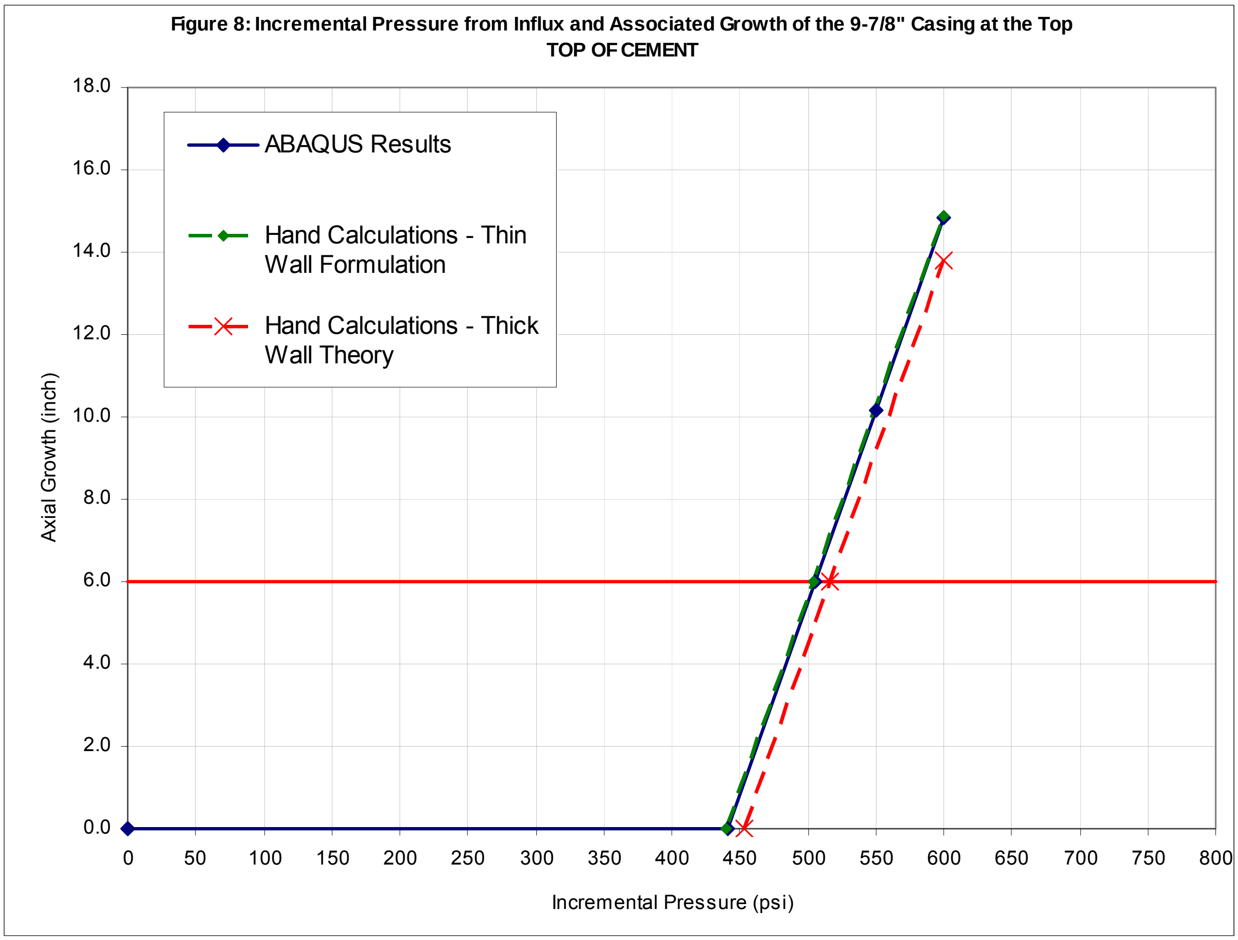

Figure 8: Graphical Representation of Results for Case 2

Case 3: Cement unable to sustain a Shear Bond

The assumption that the casing is unconstrained at the bottom of the 7-in due to the cement not being able to sustain a shear bond is considered. Note that since there is no Poisson effect, it is a matter of force balance between:

1. the submerged weight of casing.
2. the net end loads at the:
    a. Bottom of the 7-in casing assuming that the integrity of the float collar is not compromised.
    b. Crossover between the 9 5/8-in and 7-in casing
    c. Top and bottom of the seal

The net end loads are shown in Figure 9, overleaf.

Initially, the net end loads are determined by the hydrostatic head due to the fluid mud gradients at these locations; the pressure is then increased incrementally due to an assumed influx until the net loads are equal to the total submerged weight of the casing.

Using hand calculations it was determined that a pressure influx of approximately 258 psi would cause the 9 7/8-in casing/casing hanger/seal assembly to unseat from its position in the wellhead; independent calculations were also performed and the same result was determined. Moreover, this approximate value was also determined by the Abaqus model.

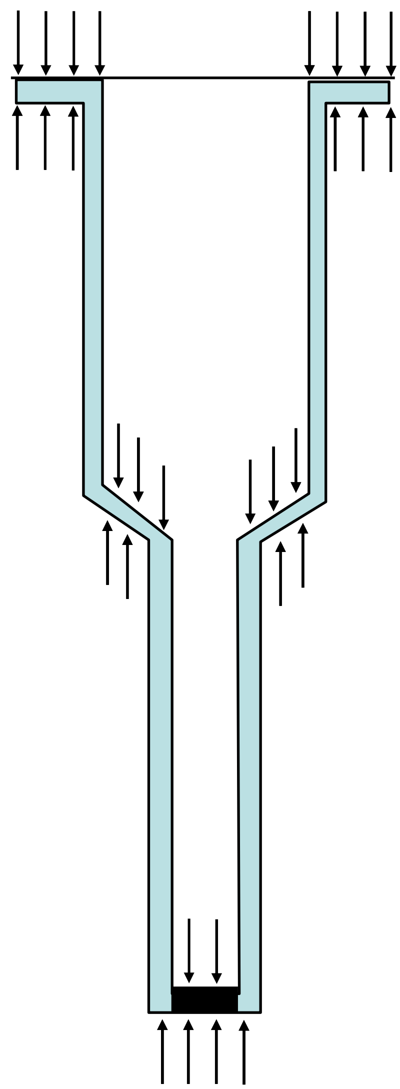

Figure 9: Case 3, Net End Loads

From the results presented in foregoing,:

a. The thin wall hand calculations are in good agreement with the results from the ABAQUS model

b. The thick walled hand calculations are also in good agreement and predict a pressure of approximately 12-psi above the thin walled hand calculations and ABAQUS results.

7.0 REFERENCES

1. Timeline Animation for 5-25-10 Presentation.ppt received from BP via J.R. Long (SES), 28th May 2010.

2. Meeting and discussion with DrilQuip and BP at SES on 17th June, 2010.